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Modeling Lake Temperature Response to Climate Change in the Alaskan Arctic

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MODELING LAKE TEMPERATURE RESPONSE TO CLIMATE CHANGE IN THE ALASKAN ARCTIC

by

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ABSTRACT

Modeling Lake Temperature Response to Climate Change

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Utah State University, 2019

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Freshwater fish are a staple in the diets of native Arctic peoples and are important for nutrition, culture, and community building. However, climate warming may affect lake temperatures and thus alter Arctic lake ecosystems and productivity. The general dearth of information on Arctic environments makes long-term forecasting of lake temperatures difficult. The two primary research questions of this study were 1) To what extent might climate warming affect water temperatures and the duration of ice in Arctic lakes? and 2) How do energy exchange processes in Arctic lakes change with warmer conditions? To answer these questions, I simulated vertical lake temperatures at a resolution of 1 m with the Freshwater Lake (FLAKE) model. I modeled lake temperature profiles and ice duration of four representative lakes at the Arctic Long-Term Ecological Research site, near the Toolik Field Station. I represented the historical period with measured input data from 1992 to 2017. I also modeled 15 future alternatives for 2006-2099 using four CMIP5 global climate models (HadGEM2-ES, CM3, CSIRO Mk3, and CanESM2) and four Representative Concentration Pathway (RCP) emissions scenarios

(RCP2.6, RCP4.5, RCP6.0, and RCP8.5). The major findings from this study are four-fold. First, Arctic lake temperatures reset each year. That is, an unusually warm or cold year did not significantly affect lake temperatures the next year. Second, June-September lake temperatures increased by 4.3-5.8 °C from the historical period with more severe climate warming (RCP8.5 scenario), but by 0.7-2.2 °C in the more optimistic RCP2.6 and 4.5 scenarios. Third, in all climate warming scenarios, the ice-off period increased in duration by at least 10 days by 2100, but by as much as 25-30 days in more extreme climate scenarios. Finally, while the timing of mixed lake conditions shifted with the timing of ice-off, the duration of mixing and onset of stratification were unaffected by warming temperatures.

(33 pages)

PUBLIC ABSTRACT

Modeling Lake Temperature Response to Climate Change
in the Alaskan Arctic

Thomas Balkcom

This thesis study focuses on simulating lake temperature and ice duration for four lakes at the Arctic Long-Term Ecological Research site, near the Toolik Field Station in Alaska. Model projections were driven by the representative global climate model outputs under different carbon emission scenarios. Results show that my simple lake model can reproduce historical lake temperature and ice duration observations, indicating the reliability of the model for future projections. Model projections show that June-September lake temperatures would increase by 4.3-5.8 °C from the historical period with most progressive carbon emission scenarios, but by 0.7-2.2 °C in the conservative scenarios. Results also indicate that in all carbon emission scenarios, the ice-off period would increase in duration by at least 10 days by 2100, but by as much as 25-30 days in the most progressive scenarios. In addition, while the timing of mixed lake conditions would shift with the timing of ice-off, the duration of mixing and onset of stratification would be unaffected by warming temperatures. This study provides important knowledge for modeling and predicting lake thermal processes for the Arctic region.

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CHAPTER 1

INTRODUCTION AND BACKGROUND

Global mean temperatures may rise as much as 4.8 °C by the end of the 21st century, and the Arctic region is anticipated to warm more rapidly (IPCC 2014). Lakes are considered sentinels of climate change because they reflect responses to climate in adjacent areas (Adrian et al., 2009). However, the environmental effects of warming on lakes in the Arctic are still largely unknown (Sorvari et al., 2002). Warming air temperatures have been observed to cause unambiguous changes in lake mixing regimes, but the effects these changes will have on metabolic energy flows and interspecies interactions are poorly understood (Mueller et al., 2009).

Some research suggests that warming may have a counterintuitive effect on lake temperatures, with the average temperature of lakes remaining unchanged due to changes in stratification. Increasing energy input may strengthen the stratification of lakes, preventing warm surface water from mixing with the cooler, deeper layer. However, as warming proceeds, this pattern may suddenly collapse, resulting in rapid warming of the deeper layer as mixing regimes shift from multiple weak mixing events to a single strong mixing event (Kirillin, 2010). Alternatively, more or higher intensity mixing events may dramatically cool overall lake temperatures.

Changes in mixing may have a strong effect on lake ice behavior, which also has a pronounced effect on lake temperatures. It is commonly known that the albedo of ice is much higher than that of water. Reduced ice cover would likely form a feedback loop, allowing the lake to absorb more solar energy and delay freezing until later in the year. When more heat is stored in the water, less ice forms or ice formation is delayed.

However, researchers believe that this energy storage has a greater influence on freeze-up dates than thawing/break-up (Brown and Duguay, 2010). Snowpack depth also influences the timing of ice cycles. Despite very high albedo, snow insulates water bodies and prevents the development of thicker ice, shortening the ice period (Brown and Duguay, 2010).

Small lake ecosystems are particularly valuable to climate research because atmospheric conditions largely drive their internal processes (Oswald and Rouse, 2004). This enables the modeler to determine with confidence whether phenomena are produced by atmospheric forcing or are internally driven (Kirillin, 2010). Additionally, small lakes reduce complexity for modelers (e.g., the lakes can be assumed to be horizontally uniform). For the purposes of this research, small lakes were defined as lakes smaller than 1 km square, as this is less than the common spatial resolution of 3-D lake models, which are more appropriate for use on larger lakes (Martynov et al., 2010). This size is also a fairly common, if somewhat arbitrary, delineation used by other researchers (Oswald and Rouse, 2004).

Freshwater fish are a diet staple for native Arctic peoples and are important for nutrition, culture, and community building (White et al., 2007). As air temperature and solar radiation continue to stray from historically measured values, the ability of Arctic lake ecosystems to provide for human needs may become degraded (Nuttall et al., 2005). The general dearth of information on these environments makes long-term forecasting of lake temperatures and fish survival difficult. Dependencies between species, warming, and biochemical interactions are not well understood (Reist et al., 2006a).

Water temperature modeling falls broadly into two categories: statistical and deterministic. Statistical methods draw results from inferred relationships between different attributes of a system based on historically observed values. This approach allows statistical models to be rapidly developed for broad areas. Deterministic models represent the known physical properties of a system. Presuming that the forces and energies acting on a water body are known, a deterministic model can represent more detailed and dynamical processes in a water body than simple statistical relationships and can predict outside the range of measured data. While a statistics-based model might provide a decent approximation of the average temperature of many lakes or across a river course based on average air temperatures, a deterministic model produces detailed estimates of water temperature at various depths. The main caveat is that the deterministic model requires more information about the energy and mass inputs to a lake system as well as physical parameters related to the lake such as depth, surface albedo, etc. (Gertsev and Gertseva, 2004). Another way to consider the difference is that statistical models are useful for estimating historical attributes of a system when relationships between a few factors are well established, while deterministic models are more apt at estimating the future responses of a lake system (Benyahya et al., 2007).

Lake model energy balance and mixing model equations have gradually advanced via iterative development. Deterministic one-dimensional (1-D) lake temperature models are separated into two groups: bulk models, and finite-difference models. Bulk models treat a water body as a single entity upon which various forces act, and finite-difference models separate the water column into many blocks of equal thickness. While finite-difference models represent more detailed mixing processes, they require more time and are vastly more computationally expensive to run. In contrast, bulk models run rapidly but sometimes fail to capture details of the water column. Compromises have been made between the two methods. The Minnesota Lake Model directly merges the two approaches, using finite blocks to determine certain values and a bulk approach to determine the more computationally intensive and chaotic conditions near the air-water interface (Stepanenko et al., 2010). Another model that uses a compromise approach is the Freshwater Lake (FLAKE) model. However, rather than directly mixing the two approaches, FLAKE simply uses a two-layer bulk model. This retains the efficiency of bulk models while allowing for more detailed representation of the processes within the water column (Stepanenko et al., 2010).

The objective of my research is to produce detailed vertical thermal profiles of four representative lakes at the Arctic Long-Term Environmental Research site near Toolik, Alaska, under historical and future climate conditions. These temperature profiles can be extracted from the output at arbitrarily fine resolutions, though for the sake of expediency I use a vertical resolution between 25 cm and 1 m. With these modeling results, I will answer two principal questions. First, how and to what extent will climate warming affect the water temperature and ice duration in these lakes? Second, how will the energy exchange processes in Arctic lakes change under warming conditions? I will quantitatively explore these two questions and related issues with the FLAKE model and observational data.

CHAPTER 2

METHODS

2.1 Model Runs

To determine differences between current and possible future lake thermal conditions, a total of 15 runs with the FLAKE model were forced with GCM outputs. Since observed weather data exist from 1992 through 2017, and GCM historical models were run to 2005, a 14-year period (1992-2005) was modeled using both observed data and historical simulations to determine how the lakes might have behaved according to observed data and the climate modeling data. I compared model runs to determine which, if any, of the climate models were most reflective of historical conditions. Model runs representing future conditions generally covered the period from 2006 to 2099. I then compared the results of these runs with modeled lake temperatures using both observed weather data and GCM historical modeled data to determine the range and extent of possible future lake temperatures and ice conditions. Additionally, actual lake temperatures were observed from 2013 to 2017, and I compared these observations with all modeled results covering this period to determine not just the efficacy of the FLAKE model but which, if any, of the GCM scenarios best reflect observed reality for the short term. The FLAKE model, input data, and model runs are described in the rest of this section.

I modeled the historical period with measured data from 1992 to 2017 and used historical data from 1992 to 2005 for each GCM. I also modeled 15 future alternatives using the four GCMs and four RCPs. In addition to future Fog Lake temperature dynamics using projected climate data, I also wanted to improve understanding of the relationship or carryover between warm lake years and cooler years. The gap-filled observed dataset was used to extract three model years: Warmest, Coldest, and Average. Years were selected using the average temperature from May through September, when lakes are typically free of ice and exposed to atmospheric conditions. These years were modeled in various permutations to determine 1) the time required to reach a new equilibrium, and 2) the time required for that new equilibrium to revert to the previous equilibrium. This analysis will help ecologists determine the effect of extreme temperature deviations on fish survival over a multiyear period.

2.2 Toolik Study Area

The Toolik Field Station and the surrounding research area are located on Alaska's North Slope at an elevation of 720 m. Air temperatures range from subzero bitter cold during the sunless winter months to almost balmy summers and shirtsleeve weather reaching 20-25 °C (EDCT, 2016). My research focused on four of the five Fog Lakes, 20 km from the Toolik Field Station. The study lakes have surface areas between about 7,000 m^2 and 50,000 m^2 and depths ranging from 10 m to 20 m (Table 1). The Fog Lakes are linked by small streams but do not have noticeable sediment input, though there is occasional thermokarst-stimulated mass wasting along the shore that may contribute to turbidity fluctuations.

Table 1. Depth and area of study lakes.

	FOG 1	**FOG 2**	**FOG 3**	**FOG 5**
Max DEPTH	19.7 m	19.7 m	20.9 m	9.9 m
Mean DEPTH	8.4 m	7.8 m	7.9 m	3.5 m
AREA	35,231 m^2	55,928 m^2	38,863 m^2	7,236 m^2
FETCH	240 m	390 m	320 m	120 m

2.3 FLAKE Model Description

Lake temperature profiles were estimated using the FLAKE model. This model was run with a daily time step over a number of multiyear scenarios. FLAKE simulates a one-dimensional vertical profile of water temperatures using atmospheric forcing and lake parameter data (Mironov, 2008). The model represents the lake's temperature profile based on a two-layer parameterization consisting of the upper mixed layer and a thermocline that extends to the bottom of the lake.

The depth of the upper mixed layer is determined by balancing two competing forces, the wind-driven turbulent mixing constrained by the buoyancy of the warmed surface water. The temperatures of the two layers are represented in the model as an energy balance and interact with each other through heat flux transfer at the interface between the two model layers. The temperature profile relies on the principle of self-similarity of temperature gradients, which for our purposes states that the shape of the thermocline can be assumed from previous empirical observations (Mironov, 2008). This principle underlies some water temperature models (Stepanenko et al., 2010). The shape of the thermocline within the FLAKE model is determined with a polynomial function. Temperature gradients within the thermally active sediment layer at the bottom of the lake and, if it exists, the surface ice layer are modeled using the same principle (Mironov et al., 2003). The model calculates surface and sediment heat fluxes, surface momentum flux, and solar energy input. Meteorological data determine the surface mass and energy fluxes (Kirillin, 2010). A more detailed description of the model's driving equations can be found in Mironov (2008), and a general description in Kirillin (2010).

Observed lake temperature profiles exist for the last three years and are used for model validation. Model fit is summarized using root mean square error and mean bias statistics. Lake temperature data were extracted from the model every 25 cm along the water column (~80 points in the deeper lakes, and ~40 points in the shallower lakes) and were interpolated based on the temperatures from the two lake layers and the temperature-depth curve.

2.4 Estimating Missing Weather Data

The field station at Toolik Lake has maintained a weather station for nearly 30 years. Unfortunately, there are numerous small gaps in the data. Some of these gaps are mere hours, while in other cases entire months are missing. To fill these gaps, I linearly interpolated between existing values when gaps were on the order of a few hours to a few days. For longer multimonth gaps, I copied values from adjacent years to fill in missing data. Fortunately, the largest gaps almost always occur in winter months when ice covers the lakes, and the lake water is less connected to the atmosphere.

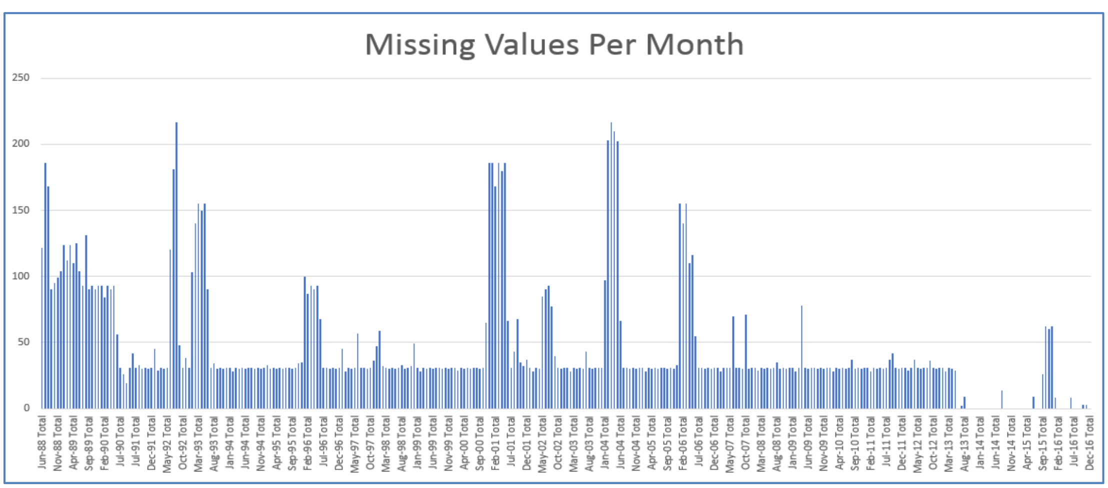

Fig. 1. The number of values missing from weather station data per month.

2.5 GCM Projection Data

The Coupled Model Intercomparison Project Phase 5 (CMIP5) is an international effort to understand and improve climate simulations and projections, with models being developed around the world. Climate data generated using four CMIP5 models were selected for use in this project (Table 2). Where possible, all four of the primary Representative Concentration Pathway (RCP) scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) have been included in this study, for 16 future climate projections. However, not every organization produces the RCP6.0 dataset at a temporal resolution that can be used for our model simulations (e.g., equal to or shorter than a daily time step), and this is noted when it was absent (Table 2).

The data extracted from GCM datasets were downscaled using a standard linear regression from the large multi-kilometer cells to the Toolik weather station point data (Dettinger et al., 2004). The historical GCM scenario for each model was used for downscaling purposes. Samples of our downscaled data are shown in Fig. 2.

Table 2. Sources of GCMs used for historical and future climate input to FLAKE.

Model	Source	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
HadGEM2-ES	Met Office Hadley Centre Earth Systems Modelling Groups, UK	√	√	√	√
CM3	Geophysical Fluid Dynamics Laboratory, US	√	√	√	√
CSIRO Mk3	Commonwealth Scientific and Industrial Research Organisation, AU	√	√	√	√
CanESM2	Canadian Centre for Climate Modelling and Analysis, CA	√	√		√

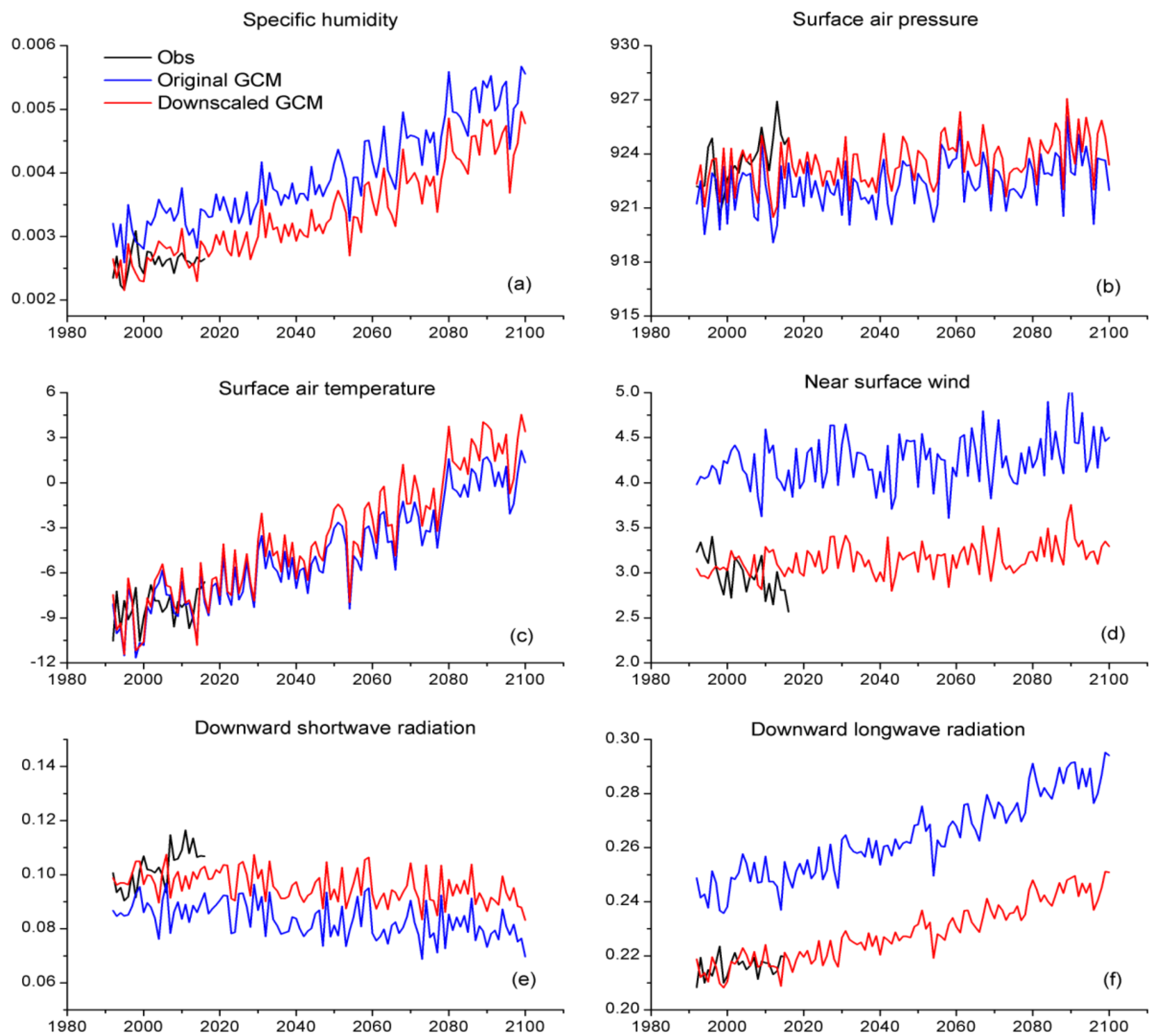

Fig. 2. Observations (black line), original (blue line), and downscaled (red line) CanESM2 data with the RCM8.5 scenario for the Toolik meteorological station. a) specific humidity; b) surface air pressure; c) surface air temperature; d) near surface wind; e) downward shortwave radiation; f) downward longwave radiation.

CHAPTER 3

RESULTS

3.1 Model Validation

Overall, the FLAKE model, which was driven by observed meteorological data, represented observed lake temperatures well. In all lakes, the total root mean square error (RMSE) did not exceed 2 °C (Table 3), but error in individual summer months peaked at ~4 °C. In all lakes, there was a persistent tendency for the model to thaw early and freeze late, but this discrepancy was usually less than two weeks in either direction. Modeled spring temperatures averaged 2.8 °C warmer than observed lake temperatures, though as the season continued, the modeled lakes returned to values more representative of observed conditions. However, it should be noted that biases at individual depths were often higher (Fig. 3). Winter temperatures were well represented in all lakes, with RMSE very rarely exceeding 3 °C.

The worst model fit was Fog 1, with an average annual RMSE of 1.2 °C. Overall, Fog 5 was modeled well, with an RMSE of 0.5 °C, particularly during the summer months (June – September), when RMSE was 0.2 °C. This may be because Fog 5 is small, and shallow compared to the other lakes. However, the relative paucity of observed temperatures during the period of observed meteorological conditions does not lend confidence to this observation. It is worth noting that more sensors have been installed in all the lakes, and a much better picture of model efficacy should be obtainable in the future.

Lake temperature error was highest near the surface (Fig. 4 and Fig. 5). The atmospheric interface is by far the most dynamic portion of the water column. Naturally, model error peaks near the surface early in the summer months, when the lake thaws due to rapid warming near the surface compared with the frozen simulation.

3.2 Downscaling Efficacy

Because the downscaled historical GCMs terminate in 2005, FLAKE model runs with downscaled data could not be directly compared with observed lake conditions. However, there was little difference in lake temperatures between downscaled climate models and raw climate models.

Table 3. Root mean square error of observed lake temperatures vs. modeled temperatures using observed meteorological conditions (2013 – 2016).

Lake	**Total RMSE over observed period, °C**	**RMSE for summer months (June – September, all years), °C**
Fog 1	1.2	1.7
Fog 2	0.1	1.1
Fog 3	0.6	1.3
Fog 5	0.5	0.2

Fig. 3. Simulation bias from observed values. a) Fog1, b) Fog 2, c) Fog 3, d) Fog 5.

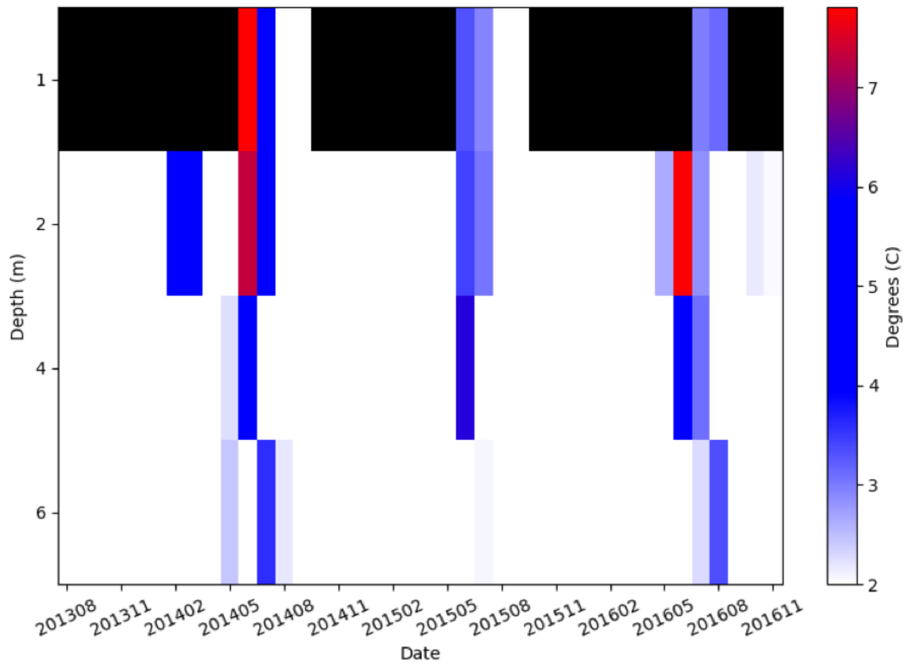

Fig. 4. Simulation biases of the temperature profile over the period of 2013 through 2016 for Fog 1.

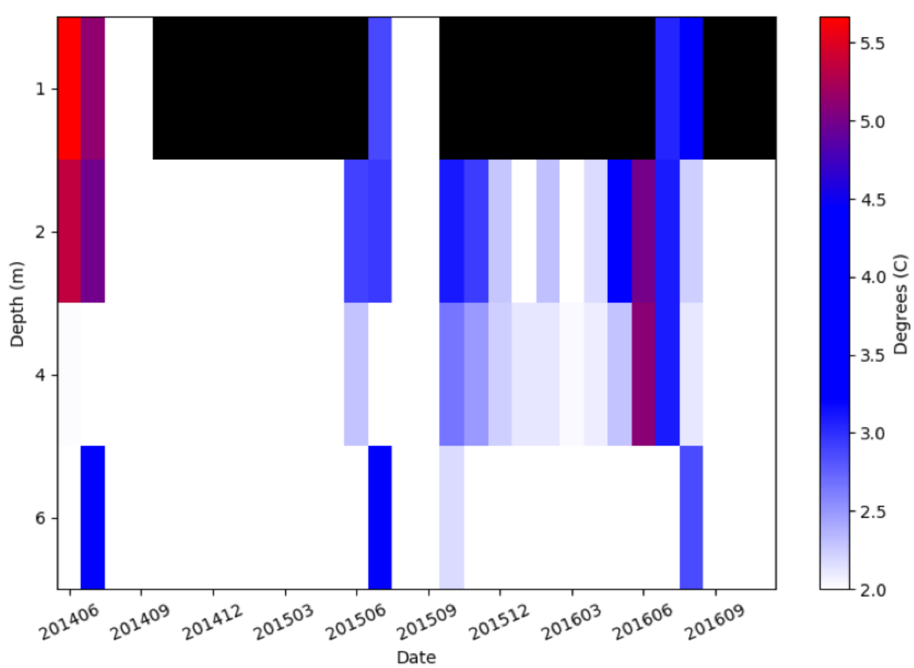

Fig. 5. Simulation biases of the temperature profile over the period of 2014-2016 for Fog 5.

Table 4. Root mean square error (°C) of lakes modeled using GCM vs. observed meteorlogical conditions.

	FOG 1	FOG 2	FOG 3	FOG 5
GFDL	1.66	1.77	1.80	2.42
GFDL *(DOWNSAMPLED)*	1.87	1.87	1.87	2.36
CANESM2	1.93	1.92	1.92	2.33
CANESM2 *(DOWNSAMPLED)*	1.80	1.88	1.87	2.38
CSIRO	1.68	1.83	1.82	2.05
CSIRO *(DOWNSAMPLED)*	1.74	1.81	1.80	2.24
HADGEM2-ES	3.99	3.13	3.12	3.96
HADGEM2-ES *(DOWNSAMPLED)*	2.87	2.96	2.96	3.65

Differences may seem higher, but it is important to note that the GCM-historic scenario is not meant to specifically mirror reality but rather to reflect general climatic conditions, so some difference in weather conditions at a specific date or time is expected and does not indicate flaws in the model. This was initially confusing due to the large difference between the raw climate data and the downscaled data for some variables such as near surface wind and longwave radiation (Fig. 2). The air temperature component was not significantly altered by the downscaling process and was a major driver of lake temperature.

3.3 Global Climate Model Results

3.3.1 Ice-Free Duration

When lake ice is modeled using historical GCM projections, the average ice duration from 1992 to 2005 is roughly 105 days. In a few of these scenarios, there is a substantial decrease in the number of days with lake ice, or in other words, more days when the lake is exposed to the atmosphere.

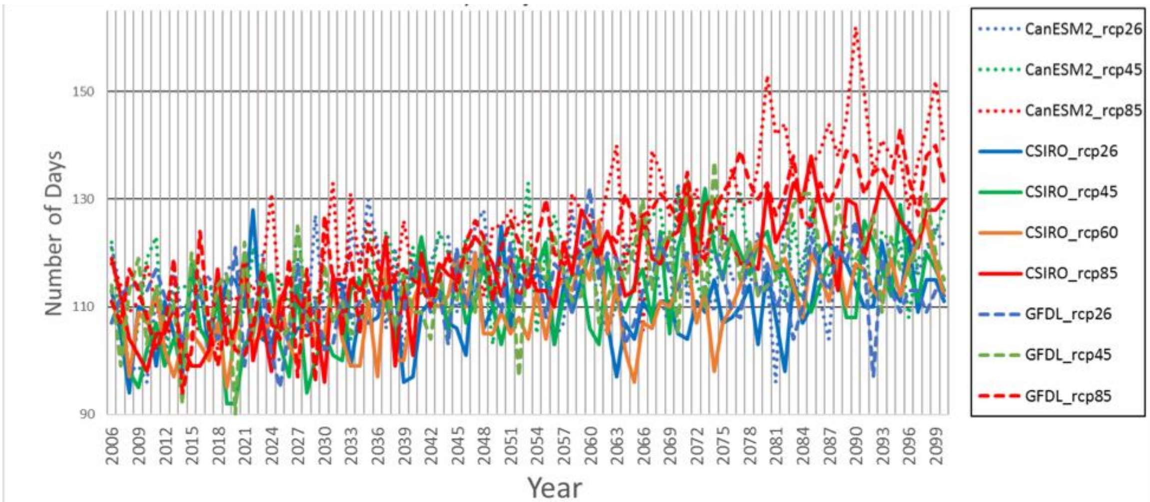

Fig. 6. Annual ice off days projected in 10 GCM scenarios.

While the RCP2.6 and 4.5 scenarios reflect the most moderate future climate changes, the warm (ice-free) season is projected to be an average of 10 days longer by 2100 across all four models. The longest warm season increases are seen in the CanESM2 RCP8.5 model in Fog Lakes 1, 2, and 3, which are larger and deeper than Fog Lake 5. The shallow Fog Lake 5 has the smallest increase in this scenario, still more than two full weeks over the modeled 1992-2005 ice-free duration. Overall, the warm season is extended among RCP8.5 scenarios by 27 days for the 2085-2100 period.

3.3.2 Lake Temperature Effects

Air temperature is the primary driver of lake temperatures and mixing. Wind has a mild effect on mixing but is overwhelmed by the dominant air temperature signal. In models using the RCP2.6 scenario, lake surface temperatures increased only ~2 °C over current norms by 2100 (Fig. 7). Maximum surface temperatures did not often increase by more than 5 °C over the present day, and then only for a few days. In contrast are the RCP8.5 scenarios, which suggest that Fog Lake surface temperatures will exceed 25 °C in the summers of the 2090s (Fig. 8). In the GFDL RCP8.5 scenario, Fog Lake 3 exceeded 24 °C in 7 of 10 years in the 2090s and exceeded 27 °C in the model year 2098, approximately 10 °C over current norms (Fig. 8).

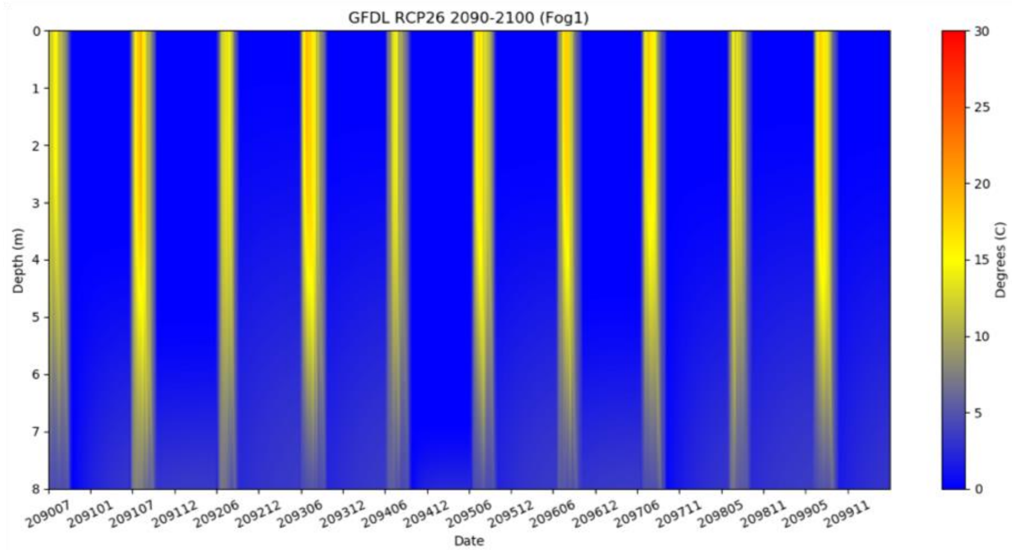

Fig. 7. Projected temperature profile with GFDL RCP 2.6 for the period of 2009-2100 (unit: °C).

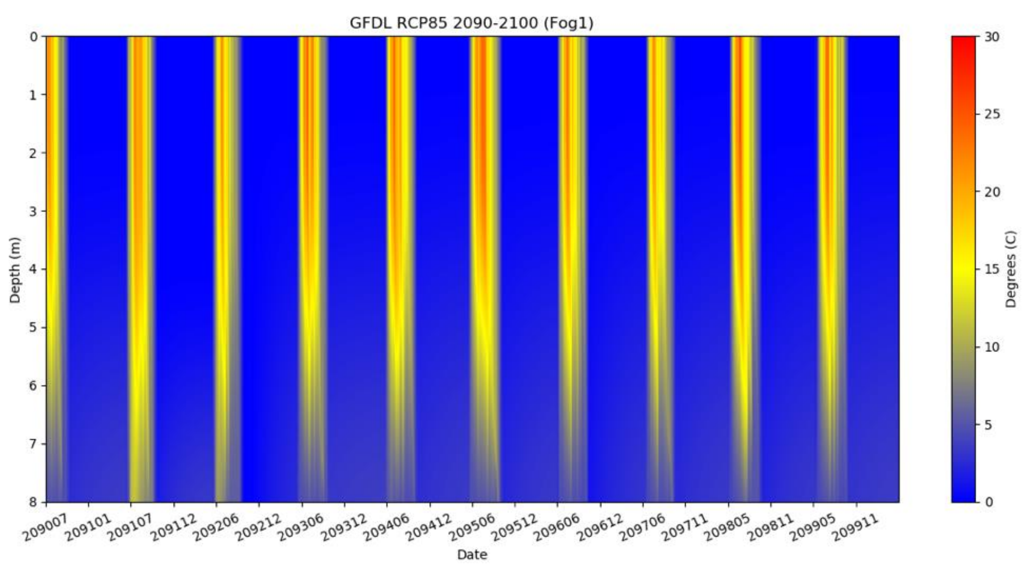

Fig. 8. Projected temperature profile with GFDL RCP 8.5 for the period of 2009-2100 (unit: °C).

3.3.3 Mixing Relationships

The models all predict a fully mixed water column during the 1992-2005 historical period for about 30 days at the beginning and end of the warm, ice-free period. This is very roughly consistent with current measured values from the actual lakes. While a small decrease in mixing duration appears to exist, it is not significant in most models or scenarios. The GCMs are not consistent with one another in this matter, though they all agree that RCP8.5 will have a shorter mixed period than RCP2.6 by 2100. In addition, Fig.10 show that the mixing layer depths will be significantly shallower projected with GFDL RCP 8.5 when compared with those for the historical period (Fig. 9). These suggest a reduction in time until stratification sets in, as well as a reduction in mixing.

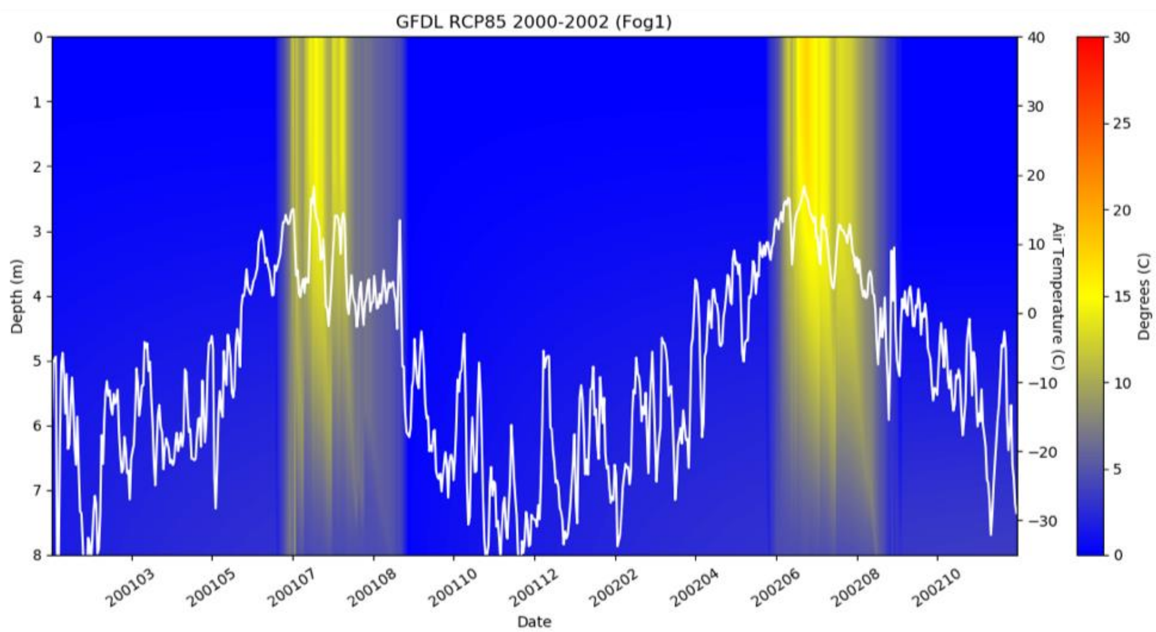

Fig. 9. Simulated temperature profile and mixing layer depth (m, white line) for the period of 2000-2002 with GFDL RCP 8.5 for Fog 1.

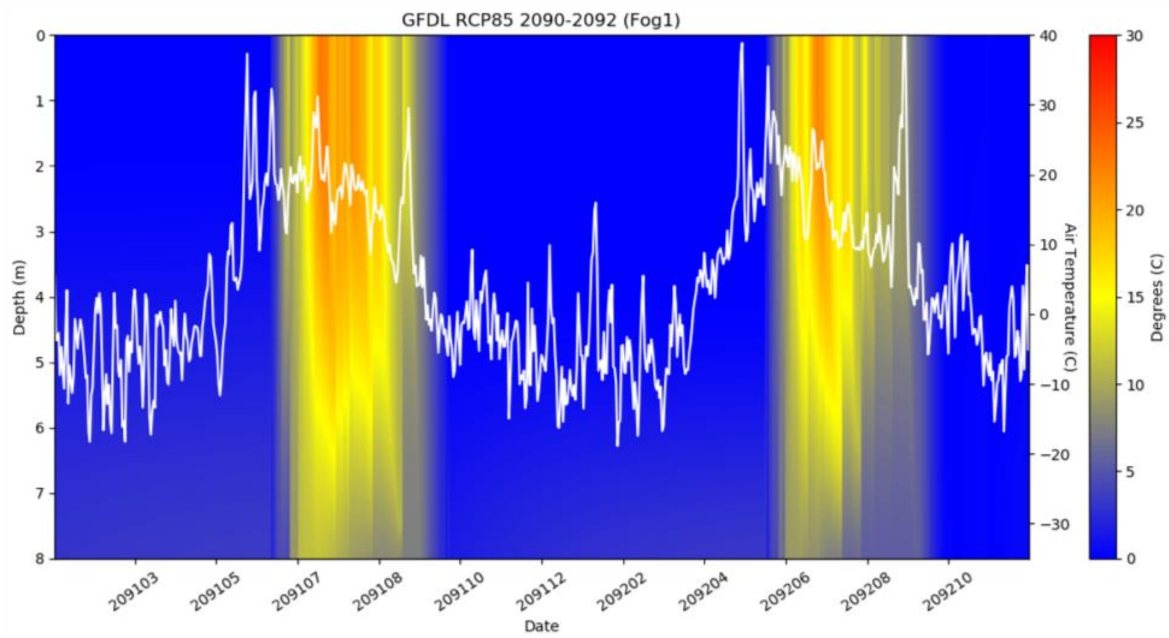

Fig. 10. Projected temperature profile and mixing layer depth (m, white line) for the period of 2090-2092 with GFDL RCP 8.5 for Fog 1.

3.4 Thermal Latency

When a historical year with deviant temperature was inserted into a sequence of index temperature years, the index year following the deviant sequence experienced a temperature deviation for one or two days before returning to normal values for the index year. This remained true regardless of whether the index years and deviant years were the warmest, coolest, or most average of the historical years modeled. Thus, this modeling suggests that shallow Arctic lakes like the Fog Lakes do not retain heat between years, and the effects of warm years do not carry into future years. Regardless, there may be a latency period in the lakes, as assumptions were made about the thermal capacity underlying the strata due to a lack of available data. That is, it was assumed that the ground beneath the thermally active lakebed maintains a constant temperature.

CHAPTER 4

SUMMARY AND DISCUSSION

The major conclusions of this study are four-fold. First, there appears to be little to no interannual latency in lake temperature. That is, an unusually warm or cold year will not significantly affect lake temperatures the next year. Second, June-September lake temperatures should be expected to increase by 4.3-5.8 °C from the historical period in the RCP8.5 scenario, but by only 0.7-2.2 °C in the more optimistic RCP2.6 and 4.5 scenarios. Third, in all scenarios the ice-off or warm period will increase in duration by at least 10 days by 2100, but perhaps by as much as 30% (25-30 days) in the most extreme scenarios. Finally, while the timing of mixed lake conditions will shift with the timing of the thaw, the duration of mixing and onset of stratification are unaffected by warming temperatures, save for a slight reduction in duration.

Like all modeling studies, this research has a number of limitations. First, a major assumption was that lakebeds have constant temperatures. It is outside the scope of this research to predict how permafrost will be affected by a warming climate. However, some thermokarst wasting was visible on the slopes surrounding at least one of the lakes in summer 2017.

The lakes’ albedo/extinction coefficient was also kept constant even though changes in precipitation, vegetation, and/or runoff might affect the amount of suspended and dissolved matter in the water column. Indeed, lake levels may rise or fall based on these factors as well. Another interesting observation was that there appears to be a substantial cooling effect on water flowing from upstream lakes to downstream lakes, where water cools several degrees during its brief time outside the lake basins.

Perhaps the most important limitation of the study is the FLAKE model's sensitivity to basin depth. This sensitivity does not allow us to directly model the deepest portions of the lake, so we must instead infer the temperatures from the water above. This also makes it difficult to understand when the lake is fully mixed, as the water column is modeled only to the average depth.

Despite these limitations, these results of climate-driven lake temperatures are generally consistent with other research (Vincent et al., 2013). The literature supports warming lake temperatures, earlier onset of stratification, and a reduction in ice duration (Prowse et al., 2011). Some authors even fear the draining and destruction of some lakes due to permafrost "breaching" events (Smith et al., 2005). Our study lakes may be vulnerable to such breaching, perched as they are on the edge of a valley.

The results of these changes are likely to have a negative impact on endemic species in Arctic lake systems in favor of more generalist invasive species (Vincent et al., 2013). Many Arctic lakes that have experienced warming in the past have seen changes in ecological organization not experienced by lakes that have not warmed. Particularly, Arctic diatoms have been shifting from benthic to planktonic preference, highlighting a major shift in the base of the Arctic food web. Research suggests that warming that has already occurred in the Arctic has largely increased productivity and diversity (Smol et al., 2005). The harsh Arctic environment becoming milder suggests that many of these increases will occur at the expense of native species (Prowse et al., 2006). Everything from reductions in thermal refugia to possible algal blooms caused by increased solar input due to icing changes has been suggested, though there is a great deal of variation in how species will be helped or harmed by changing conditions (Reist et al., 2006b). The continued warming anticipated by this research suggests that alterations in Arctic ecology will continue and perhaps even accelerate.

In the future, better metrics to describe thermocline mixing should be devised to better quantify changes over time. Also, a detailed inquiry into the potential effects on the ecological system of changes in ice cover, temperature, and mixing behaviors detailed by this study will surely serve to enhance our understanding of the changing Arctic landscape.

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